Observational and Theoretical Foundation for the Dynamics in a High-resolution Sea Ice Model

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LONG-TERM GOALS

The overall goal of this collaborative effort is to provide the observational and theoretical foundation for ice dynamics in a high resolution sea ice model, PIPs 3.0, based on the concepts of sliplines and granular plates and the use of direct field measurements and remote sensing assets.

OBJECTIVES

There are 3 main objectives in this project:

- Further understand the scale interaction between the multiple floe scale (<10 km), the regional granular continuum scale (10-200 km), and the sub-basin scale (>200 km).
- Understand the stress propagation through sea ice by direct measurements from a regional stress array (50-200 km), and use results to estimate the ice strength parameter, P*.
- Create at least five test cases for model evaluation.

APPROACH

Our approach is based on the fundamental assumption that regional ice motion is controlled by a system of sliplines and aggregate plates, made of individual ice floes. This assumption is the result of insights gained from observations made during the Sea Ice Mechanics Initiative (SIMI) and the Surface Heat Budget of the Arctic Ocean (SHEBA) field programs (Richter-Menge and Elder,1998; Overland et al., 1998). These observations were derived from stress and deformation arrays and satellite-derived motion vectors. The objective of this effort is to further assess the validity of this concept and extend it to the basin scale. A number of coordinated activities are underway to achieve this objective: a)

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continued analysis of the SIMI and SHEBA data sets, b) deployment of another stress and deformation buoy array, and (c) application of a host of remote sensing tools. Test cases for the evaluation of the PIPs 3.0 model are chosen by studying these combined resources to determine periods of significant ice motion activity. Observations and model results are compared by considering the individual components of the stress divergence term, which include the effects of normal compression, shear stresses, curvature of the sliplines, and hardening of the ice cover in response to continued wind forcing.

In addition to extending the scale of our direct observations of stress and deformation, the buoy array is designed to provide information on the ice strength parameter, know as P* . P* is a key component in the PIPs and other sea ice dynamics models, as it determines when ice failure occurs in the model. The buoy array has been designed to measure the speed of the compressional waves during convergence of the ice cover against a coastal boundary, to give a direct estimate of P*.

WORK COMPLETED

A journal article on the role of the summer ice dynamics in the surface heat budget has been published (Richter-Menge et al., 2001), the final galleys for a journal article on the relationship between in situ measurements of ice stress and satellite-derived ice motion observations at the regional scale have been submitted for publication (Richter-Menge et al, in press), and a conference paper describing the early results from a stress and deformation array, which was deployed in September 2001 and collected data through May 2002, has been completed and accepted for publication (Richter-Menge et al., accepted).

A journal article that defines a classification for Arctic sea ice dynamics, based on spatial and temporal scales, is nearing publication (McNutt and Overland, in press).

We successfully deployed a set of 9 autonomous buoys in the Beaufort Sea pack ice in September 2001, using the *CCCS Sir Wilfrid Laurier* as a base of operations. This array included 9 stress/position ARGOS drifting buoys, one meteorological station and one ice mass balance station (Perovich and Elder, 2001). Measurements of ice stress and deformation were collected into April 2002.

In support of the buoy array, all the SAR imagery for 2001-2002 was ordered, processed and received.

A GIS-based tool was developed for the presentation and analysis of the buoy data.

RESULTS

The most significant technical achievement during this review period is the collection of a new data set on sea ice stress and deformation, for the development and validation of sea ice dynamics models. This data set is derived from an array of autonomous buoys and satellite imagery. Data from the buoy array include direct internal ice stress measurements suitable for comparison with model-computed values. They also provide measurements of the movement of the ice pack with a high spatial (10 km) and temporal resolution (hourly), consistent with the predictive needs of the Navy's operational models. The unique features of the array deployed in September 2001 were its large areal extent (200 km) and its orientation in a north-south direction, perpendicular to the North Alaskan coast. These characteristics were selected to provide insight on the areal extent of the aggregate behavior of the ice pack and to test the hypothesis that, during a loading event, stress propagates outward from the coast, producing a compressional wave. Data from the buoy array and satellite imagery allow for the direct

evaluation of the ice rheological components of sea ice dynamics models. Currently, the ice rheology is inferred by comparing modeled ice motion with data from ice drift tracks.

The stress and deformation buoy array was deployed in September 2001 and collected data through May 2002 (Figure 1). This array was designed to build on our previous work in SIMI (Richter-Menge et al., 1998 and Overland et al, 1998) and SHEBA (Richter-Menge et al, in press). It was purposefully located in roughly the same region as the stress and deformation arrays deployed during SHEBA and SIMI arrays, since one of our objectives was to observe the level of consistency in the loading conditions and the associated mechanical response of the sea ice cover in this region of the Arctic.

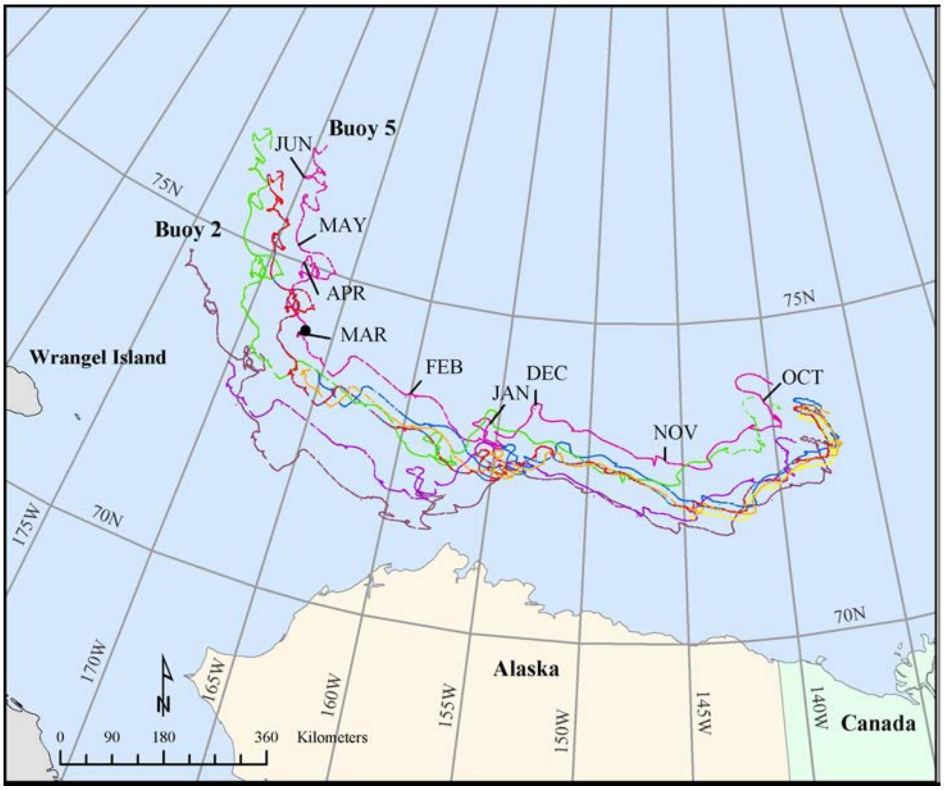

Figure 1. Drift tracks of buoys installed in late September 2001, showing a rapid westward drift until December and, then, a gradual increase in the northerly component of the drift. The record ends in June 2002.

The drift track of the buoys (Figure 1) provides strong evidence that there is significant coherency in the pack over distances of up to 200 km. In general, the buoys moved in concert, including the display of very intricate and consistent patterns. For instance, at the beginning of January, all the buoy moved in a clockwise loop, elongated in the East-West direction. Clearly, the components of the sea ice cover in this region are moving as an aggregate. This results is consistent with our finding in SIMI and SHEBA and further supports our fundamental hypothesis that the sea ice cover behaves as a granular plastic, where the fundamental component is the ice floe. The system's plasticity is established by the interaction of the floes, which move together in aggregate plates separated by narrow sliplines.

The average in situ stress measured by the buoys in the array between 22 September 2001 and 8 April 2002, is presented in Figure 2. Most notable in this time series is the gradual, but marked increase in

the underlying stress beginning in mid-November. Up until mid-November, between stress events the stress returns to near zero. By the beginning of March the baseline stress has increased to 20 kPa. While more pronounced in this experiment, compared to SIMI and SHEBA, this result is consistent with our earlier findings. We believe that this gradual increase in the underlying stress reflects an increase in the compressive failure strength of the ice cover. Combined with information from the drift track, we further hypothesize that mechanical thickening of the ice cover played a significant role in the increase of the compressive failure strength.

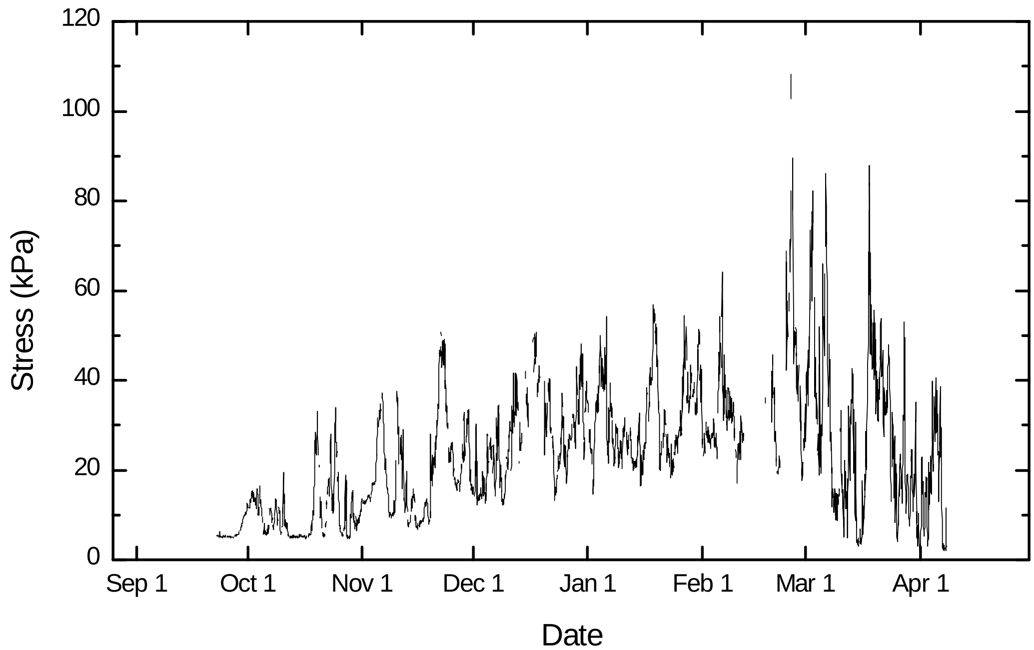

Figure 2. Time series of the internal ice stress between 22 September 2001 and 8 April 2002, showing episodic stress events, lasting for 3-10 days, under laid by a gradual increase in the baseline stress, from 0 kPa in early November to 20 kPa in early March.

The consistency between the fundamental aspects of the ice behavior during the 2001-2002 experiment and the SIMI and SHEBA experiments is satisfying. These reproducible results validate this measurement techniques and the ensuing data sets and reinforce our fundamental working assumption that the rheology of the ice cover can be determined through direct measurements.

Well beyond the contributions from the earlier data sets, the data collected during the 2001-2002 experiment provide new breakthroughs in our conceptual insight on the rheological behavior of the sea ice cover, including the impact of scale and the influence of temporal and spatial variations in the thickness distribution of the ice cover. The design of the array and the success of the experiment will also permit a more rigorous evaluation of sea ice dynamics models, in support of Navy operations at high latitudes.

IMPACT/APPLICATION

The result of a measurable relationship between ice stress and deformation is a strong indication that our goal of applying direct observation from field measurements and satellite imagery to validate the model results from PIPS 3.0, and other high-resolution models, is achievable. We are specifically interested in considering the rheology used to describe the mechanical behavior of the ice cover, which is a fundamental component of the model's governing equation. Direct validation of the rheology is likely to lead to improved modeling capabilities, including increased model resolution. We will focus our evaluation on the 9 km grid resolution/multi-thickness version of the developing PIPS3 model. A workshop on sea ice dynamics, held in 2000 (Overland and Ukita, 2000), suggested that this level of physics is important to resolve regional (50-300 km) processes.

TRANSITIONS

These results will be used to develop and validate the latest version of the Navy's Polar Ice Prediction System model. We are working directly with the modelers involved in this project to determine and assess validation tests.

RELATED PROJECTS

1) N00014-02-1-0244, Stochastic Analysis of Satellite-Derived Arctic Sea-Ice Information. Data collected from the stress and deformation arrays deployed during SIMI, SHEBA and, most recently, the September 2001 deployment serve as the foundation for this project. The overall goal of the project is to undertake a rigorous analysis of satellite-derived data, especially SAR, compared to *in-situ* observations. By using a stochastic method to study datasets at various spatial and temporal resolutions, we will provide a measure of error analysis for the assimilation of satellite-derived data products intended for use in the upcoming PIPS model.

2) SHEBA ice stress and deformation measurements are also being used in the SHEBA project, which is focused on improving models of climate variability. The SHEBA program is sponsored by NSF and ONR. Our work in this program is focused on improving the understanding of the processes that govern ice motion, which are important for determining the thickness distribution of the ice cover. The thickness distribution of the ice cover has a significant impact on heat and energy exchange between the atmosphere, ice, and ocean.

3) One of the PIs (JR-M) is working with Mark Hopkins (CRREL), who is receiving support from NSF and NASA to continue development of a discrete element model of the ice cover. This model is unique in its ability to consider floe-floe interactions and provide a more detailed characterization of ice distribution.

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